

Potential Synergistic Effects of Cereal Rye Biomass and Soybean Planting Density on Weed Suppression

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Increasing crop density is a cultural weed management practice that can compliment the use of cover crops for weed suppression. In this research, we created a range of cover crop biomass and soybean densities to assess their weed-suppressive ability alone and in combination. The experiment was conducted in 2008 and 2009 in Maryland and Pennsylvania using five levels of cereal rye residue, representing 0, 0.5, 1.0, 1.5, and 2.0 times the ambient level, and five soybean densities ranging from 0 to 74 seeds m^{-2} . Weed biomass decreased with increasing rye residue and weeds were completely suppressed at levels above 1,500 g m^{-2} . Weed biomass also decreased with increasing soybean density in 2 of 4 site-years. We evaluated weed suppression by fitting an exponential decay model of weed biomass as a function of rye biomass and a hyperbolic model of weed biomass as a function of soybean density at each of the five tactic levels. We multiplied these individual tactic models and included an interaction term to test for tactic interactions. In two of the four site-years, the combination of these tactics produced a synergistic interaction that resulted in greater weed suppression than would be predicted by the efficacy of each tactic alone. Our results indicate that increasing soybean planting rate can compensate for lower cereal rye biomass levels when these tactics are combined.

Nomenclature: Cereal rye, *Secale cereale* L.; soybean, *Glycine max* (L.) Merr.

Key words: Cover crops, synergism, cultural weed management, organic.

Tillage provides several important benefits in cropping systems, which is why it has been so widely used in agriculture (Lal 2009). Tillage mixes and buries soil amendments and crop residue, eliminates existing vegetation, reduces pest populations (Govaerts et al. 2007; Norris 2005), promotes mineralization of soil organic matter, and creates a seedbed that facilitates mechanical planting and seed-to-soil contact. However, tillage can also result in increased soil erosion and surface water eutrophication (Choudhary et al. 1997; Lal et al. 2007). During the past 30 years, much progress has been made in reducing tillage. No-tillage crop production has increased 2.5-fold from about 45 million ha worldwide in 1999 to 111 million ha in 2009 (Derpsch et al. 2010). One downside of this trend is increased use of herbicides for weed suppression (Montgomery 2008).

In organic cropping systems, where herbicides and mineral fertilizers are prohibited, weed suppression must be achieved by means other than synthetic herbicides. Even with tillage, weed management in organic cropping systems remains a significant challenge (Ryan et al. 2007). Despite the beneficial role that tillage plays, organic farmers have indicated that the development of strategies for reducing tillage is a high research priority (Francis 2002; Sooby et al. 2007). Although continuous no-till is challenging in organic cropping systems because of perennial weeds (Berner et al. 2008; Peigne et al. 2007; Teasdale et al. 2007b), interest in reducing tillage among organic farmers remains high.

Tillage can be reduced by incorporating perennial crops like alfalfa (*Medicago sativa* L.) into crop rotations, thereby reducing tillage frequency. A second strategy is to reduce the intensity of tillage by using a chisel plow instead of a moldboard plow (compromise between full inversion and no-till). A third strategy is to reduce tillage by no-till planting of cash crops into mechanically killed cover crops, which serve as

a weed-suppressive mulch. In such cases, tillage is limited to establishing cover crops (Mirsky et al. 2009; Mischler et al. 2010a). This last strategy provides a reduction in tillage frequency by rotating between cash crops that are no-till planted and cover crops that are established with tillage; hence, the term *organic rotational no-till*. Roller-crimpers are commonly used to kill winter annual cover crops before no-till planting of cash crops and have been shown to facilitate weed suppression by creating a more uniform mulch layer (Davis 2010; Mirsky et al. 2009; Mischler et al. 2010b).

Cover crops can be an important component of ecological weed management (Mohler and Teasdale 1993; Teasdale et al. 2007a) and can also provide ecosystem services, such as reducing soil erosion and nutrient leaching (Snapp et al. 2005). Cover crops can enhance weed suppression in a number of important ways. They limit light and nutrient availability through competition; they can be used as mulch to physically suppress emerging seedlings; they limit soil warming, thus delaying weed seed germination; and some cover crop species produce germination-inhibiting secondary plant metabolites (Davis and Liebman 2003; Shearin et al. 2008; Teasdale and Mohler 1993; Teasdale et al. 2007a). Cover crops can also have indirect effects, such as providing habitat for weed-seed predators. The weed-suppressive role of cover crops in conventionally managed no-till corn (*Zea mays* L.) and soybean has been well studied (Duiker and Curran 2005; Fisk et al. 2001; Gallagher et al. 2003; Williams et al. 2000), and increasingly, there is more information on using cover crops for no-till weed suppression in organically managed systems.

Increasing crop interference with weeds by increasing crop seeding density and spatial uniformity can be an effective cultural weed management tactic (Hock et al. 2009; Jordan 1993; Weiner et al. 2001). In a recent study comparing four soybean seeding rates (24, 30, 36, and 42 seeds m^{-2}) in Iowa, seeding rate was shown to be inversely related to weed biomass (Arce et al. 2009). Soybean yield was greater in the highest seeding rate compared with the lowest. In organic systems, increasing soybean seeding rate can be an effective tactic for reducing weed abundance (Place et al. 2009). In an

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experiment comparing four soybean seeding rates (19, 31, 43, and 56 seeds m^{-2}), percentage of weed cover was negatively correlated with soybean seeding rate at three of five study sites. Percentage of weed cover at the highest seeding rate was less than half that observed at the lowest rate and was accompanied by increased soybean yields (Place et al. 2009).

Antagonistic interactions have been demonstrated between cultivation and cover crop mulch efficacy because mulch can decrease the effectiveness of some cultivation implements. In one experiment, cultivation efficacy was 38–69% in reduced tillage treatments, compared with 87–95% in tilled treatments (Teasdale and Rosecrance 2003). Preferably, multitactic weed management should employ combinations of cultural weed management practices that result in synergistic interactions. Previous research has demonstrated a synergistic interaction between hairy vetch (*Vicia villosa* Roth) residue and the herbicide metolachlor (Teasdale et al. 2005). In that case, the mechanism responsible for the synergistic response was thought to be a mulch-induced carbohydrate deprivation of the etiolated seedlings, which prevented sufficient detoxification of the metolachlor at low rates. This was one of the first documented cases of synergism involving a cultural weed management tactic.

In this article, we report on an experiment in which we quantified weed suppression from increasing soybean crop seeding rate and biomass from a cereal rye cover crop. Our experiment was designed to model response surfaces of weed biomass from tactical combinations. Combinations of these tactics are particularly important because early season weed suppression from rye cover crop residue could delay weed establishment until the soybean leaf canopy becomes sufficiently suppressive, and late-season weed suppression from a high-density soybean canopy could suppress weeds not controlled by residue. Therefore, we hypothesized that there would be a synergistic interaction, where cereal rye residue would weaken emerging weeds and enhance their suppression by the more competitive soybean leaf canopy.

Materials and Methods

The experiment entailed planting a cereal rye cover crop in the fall. In the following spring, the rye was clipped and removed from the plots, the weed seed bank was supplemented with additional weed seeds, and soybean was seeded at a range of rates. The clipped rye biomass was then returned to the plots at varying levels. Although this methodology may seem academic, it eliminates any potential confounding effects related to planting soybean through a wide range of rye residue levels. Crop seed placement in high-residue environment is a separate issue that deserves further attention. Metrics of soybean performance and weed suppression were collected during the summer and fall.

The experiment was conducted at the Beltsville Agricultural Research Center in Beltsville, MD, in 2008 and 2009, at the Rodale Institute in Kutztown, PA, in 2008, and at the Russell E. Larson Agricultural Research Center in Rock Springs, PA, in 2009. In Maryland, the experiment was conducted on a Matawan–Hammonton loam sand in 2008 and a Codorus–Hatboro silt loam in 2009. In Pennsylvania, the experiment was conducted on Berks shaley silt loam in 2008 and on Hagerstown silt loam in 2009. The Pennsylvania 2008 site was managed organically for approximately 30 years, whereas

the other sites had not been managed organically in the past. Soil pH in all site-years was between 6.5 and 6.7. Soybean seeding and cereal rye mulch rate were experimentally manipulated to achieve five levels of each and were arranged in a randomized complete split-block design. Soybean seeding and rye mulch rates were combined in a factorial arrangement, resulting in a matrix of 25 experimental units, which were replicated four times ($n = 100$). We targeted at 0 \times , 0.5 \times , 1.0 \times , 1.5 \times , and 2.0 \times the typical soybean seeding rates (37 seeds m^{-2}) and the same range for the aboveground rye biomass (1.0 \times is typically 600 to 1,000 g m^{-2}). Experimental units were 3 m \times 4.6 m, except for Maryland in 2008, where the plot size was 3 m \times 3 m. Alleyways between plots were maintained by mowing.

Cereal rye (*Secale cereale* L. cv. 'Aroostook')¹ was seeded with a drill at 135 to 200 kg ha^{-1} at each site-year between October and December of 2007 and 2008. This cultivar was selected because it performed well in previous research (Mirsky et al. 2009). In early June, at all locations, the rye cover crop was cut and windrowed using a haybine from a 4.3-m swath that was compressed using hand rakes to a 1.2-m-wide windrow. Rye was between 1.5 and 2 m tall and was in the anthesis or early milk stage of development when cut.

Plots were demarcated between windrows using flags and supplemented with weed seeds to ensure greater homogeneity of weed abundance. In Maryland, giant foxtail (*Setaria faberi* Herrm.) and smooth pigweed (*Amaranthus hybridus* L.), were supplemented at 1,000 seeds m^{-2} species⁻¹. The 2008 Pennsylvania field site was supplemented with common ragweed (*Ambrosia artemisiifolia* L.), redroot pigweed (*Amaranthus retroflexus* L.), giant foxtail, and common lambsquarters (*Chenopodium album* L.) at 1,000 seeds m^{-2} species⁻¹. In 2009, the Pennsylvania field site was supplemented with common ragweed, smooth pigweed, giant foxtail, common lambsquarters, and velvetleaf (*Abutilon theophrasti* Medik.) at 500, 350, 1,000, 1,000, and 150 seeds m^{-2} , respectively. Weed seeds were collected from research farms in Pennsylvania and Maryland. Weed seed supplementation varied slightly across site-year because of a lack of locally collected seed. However, our intention was to ensure adequate weed propagule pressure for testing tactics under weed population conditions that may be encountered on organic farms and thus do not consider this to be a hindrance to testing our hypothesis.

Following seed bank supplementation, rhizobium-inoculated soybean (Blue River 2A12 - group 2.1 maturity)² was planted with a drill,³ calibrated to deliver 19, 37, 56, and 74 seeds m^{-2} into rye stubble, between windrows. An unseeded control treatment was also included. Rye residue was then spread back onto plots following soybean planting. Rye residue was placed on top of the seeded plots at five rates. The 1.0 \times rate was the quantity spanning the linear windrow length of the plot (i.e., the material removed from that plot area by haybining). The 0.5 \times rate was derived from half the linear windrow length of the plot, with the remaining residue used to supplement the 1.5 \times rate. Finally, the linear windrow length of the 0 \times plot was used to supplement the 2.0 \times plots.

At approximately 1 wk after soybean planting, rye mulch mass was determined in each plot by removing the rye residue in 0.25- m^2 quadrats, oven-drying the residue at 50 C for approximately 1 wk, then weighing. Rye stubble was also collected from the 0 \times mulch rate treatments in all site-years, except in 2008 at the Pennsylvania site. Soybean density and

weed biomass were assessed approximately 15 wk after planting by counting soybean plants in a 0.5-m² quadrat. Weeds were clipped, oven-dried (as above), and weighed.

Single Tactic Models. The weed-suppressive effect of soybean density was quantified by regressing weed biomass against soybean density using the following hyperbolic model:

$$W = w_0 \{1/[1 + (i \times S)]\} \quad [1]$$

where W is the weed biomass (g m⁻²), w_0 is the intercept (g m⁻²), i is the soybean competition coefficient (m² plant⁻¹), and S is the soybean density (plants m⁻²). The weed-suppressive effect of a soybean plant was expressed as the parameter i , which describes the initial slope of the hyperbolic function and thus the fractional reduction in weed biomass per soybean plant (Spitters 1983).

The weed-suppressive effect of rye biomass was fit using an exponential decay model, which has previously been used to fit data of this kind (Teasdale and Mohler 2000). The exponential decay model as a function of rye biomass follows:

$$W = w_0 (e^{-b \times R}) \quad [2]$$

where b is the rye suppression coefficient (m² g⁻¹), and R is the rye biomass (g m⁻²). Because low (< 200 g m⁻²) mulch rates can stimulate weed biomass (Teasdale and Mohler 2000), particularly in coarser soils, an additional term was added to Equation 2 to describe the positive mulch response:

$$W = w_0 (1 + m \times R) (e^{-b \times R}) \quad [3]$$

where m is the rye stimulation (m² g⁻¹). The m parameter, describing the positive relationship between weed biomass and rye mulch rate, was only included if the estimate was positive and significant.

Multitactic Models. We assumed that the effect of soybean density and rye biomass combined multiplicatively. A multiplicative model for the combined action of two factors assumes that the factors act independently and have different mechanisms of weed suppression. It is assumed that the models for each factor acting alone will adequately describe their activity when acting together and that there are no additional interactions that need to be accounted for. Thus, the multiplicative model simply multiplies the models that define the activity of each factor. The multiplicative model was the product of Equations 1 and 2, written as follows:

$$W = w_0 \{1/[1 + (i \times S)]\} (e^{-b \times R}) \quad [4]$$

The hypothesis of this research was that soybean density and rye biomass do not act independently according to this purely multiplicative model, but rather that rye biomass provides soybean with a competitive advantage over emerging weeds and that soybean leaf canopy from a high-density planting suppresses weeds that otherwise would escape control by rye residue. Thus, an alternative to the multiplicative model (Equation 4) was developed that included an interaction parameter representing the synergistic deviation of these jointly acting factors. This expanded model is written as follows:

$$W = w_0 \{1/[1 + (i \times S)]\} (e^{-b \times R}) (e^{-d \times R \times S}) \quad [5]$$

where d is the interaction parameter (m⁴ plant⁻¹ g⁻¹). Models were compared for each site-year, and the best-fit model was

selected based on Akaike's information criterion (AIC) values (Johnson and Omland 2004). If a more complex model resulted in a reduction of the AIC value of at least 2, then it was selected. The ANOVA function in R statistical software⁴ was also used to compare competing models using an F test. Deviation from the multiplicative models when the interaction parameter was significant was a final test used to detect the presence or absence of synergism. This approach was previously used to test for synergism between metolachlor and hairy vetch residue (Teasdale et al. 2005).

In cases where there was a positive weed response to low levels of mulch, we used a different set of equations to test for a synergistic interaction. These models accounted for the positive weed response and resulted in a better fit. The two-factor reference multiplicative model in such cases was the product of Equations 1 and 3 and is defined as follows:

$$W = w_0 \{1/[1 + (i \times S)]\} (1 + m \times R) (e^{-b \times R}) \quad [6]$$

This reference model was compared with a two-factor interaction model that included the d parameter as follows:

$$W = w_0 \{1/[1 + (i \times S)]\} (1 + m \times R) (e^{-b \times R}) (e^{-d \times R \times S}) \quad [7]$$

Similar to the set of equations that did not include an m parameter, the two-factor interaction model was compared with the reference model using the same criteria.

Data Analysis. Curve fitting was performed using the nonlinear least squares (NLS) function in the R software. Data were plotted to visualize the response surfaces, and models were fitted to analyze the relationship between rye biomass, soybean density, and weed biomass. Weed-suppression models were fit to data for each site-year separately because of differences in resident weed communities and resulting infestation levels, soils, and weather.

Isobols for Evaluating Tactic Combinations. Interaction models across site-years can be evaluated by comparing weed-biomass isobols (or isolines) from each model in a bologram (Laska et al. 1994; Morse 1978). This approach identifies combinations of each factor (soybean density and rye biomass) that are equally weed suppressive. For this analysis, we standardized across site-years by using the average weed-biomass level for all treatments within a site-year as an indication of the environmental mean weed biomass. This provided a reasonable assessment of specific site-year weed abundance. We then used the estimated parameters for each tactic to solve for the quantity of rye biomass and soybean seeding rate that results in a 25% and 50% reduction of weed biomass, and that procedure was performed separately for each site-year. These values were then plotted as isobols, which depict the combination of tactic levels resulting in 25% and 50% suppression of weed biomass. For example, if the mean weed biomass across all experimental units at Maryland in 2009 was 156 g m⁻², the 50% isobol would represent the rye biomass and soybean density required to result in a weed biomass of 78 g m⁻².

Results and Discussion

Weed biomass ranged from 0 to 967 g m⁻² across all site-years. The highest levels of weed biomass were observed at the

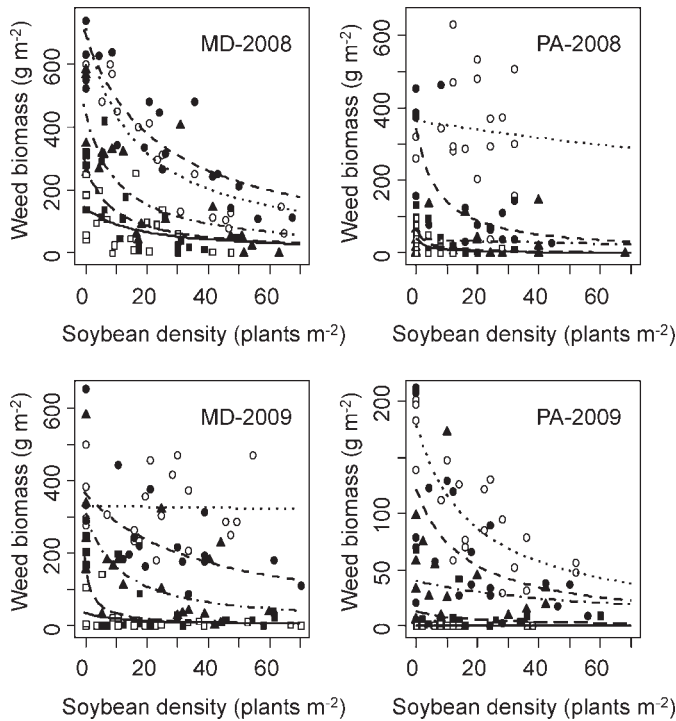


Figure 1. Symbols represent measured weed biomass, and soybean density coordinates and lines represent fitted models for each of the five targeted rye-mulch rates (\circ dotted, 0; \bullet short dash, 0.5 \times ; \blacktriangle dot-dash, 1 \times ; \blacksquare long dash, 1.5 \times ; and \square solid line, 2 \times ambient mulch level) across site-years (upper right of each panel). Note the scale of the y-axis differs between site-years. All data were used for regression analyses; however, axis scales were restricted to illustrate relationships at reasonable soybean density levels, and thus, some extreme data points are not represented.

Maryland site in 2008 (mean = 246 g m⁻²), whereas the lowest levels were observed at the Pennsylvania site in 2009 (mean = 42 g m⁻²). More than 75% of the weed biomass was composed of giant foxtail, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], smooth pigweed, and yellow nutsedge (*Cyperus esculentus* L.) in Maryland in 2008; giant foxtail and smooth pigweed in Maryland in 2009; giant foxtail, common ragweed, and redroot pigweed in Pennsylvania in 2008; and common ragweed, eastern black nightshade (*Solanum ptycanthum* Dunal), cereal rye, velvetleaf, yellow foxtail [*Setaria*

glauca (L.) Beauv.], redroot pigweed, and giant foxtail in Pennsylvania in 2009.

Effect of Soybean Density on Weed Biomass. Soybean density ranged from 0 to 75 plants m⁻² across all site-years (Figure 1). Mean soybean density was slightly greater at the Maryland sites (22 plants m⁻²) compared with the two Pennsylvania sites (14 plants m⁻²). In the absence of cereal rye (0 \times), weed biomass was reduced by 56, 10, 11, and 31% in the 56 seeds m⁻², compared with the 37 seeds m⁻² treatments in Maryland in 2008, Maryland in 2009, Pennsylvania in 2008, and Pennsylvania in 2009 site-years respectively. This illustrates the potential for weed suppression by increasing soybean seeding rate 50% greater than the standard of 37 m⁻². In Maryland in 2008 and Pennsylvania in 2009, soybean density accounted for between 70 and 85% of the variation in weed biomass, and the *i* parameter ranged from 0.053 to 0.062 m² g⁻¹ (Table 1). Greater *i* parameter estimates indicate a greater reduction in weed biomass from soybean density. More rapid establishment and early growth of weeds may have contributed to the relatively low weed suppression from soybean in Maryland in 2009 and Pennsylvania in 2008.

Effect of Rye Biomass on Weed Biomass. Rye mulch rate resulting from our treatment manipulations ranged from 0 to 4,871 g m⁻² across all site-years. The mean rye mulch rate was approximately double at the Pennsylvania sites (1,286 and 1,038 g m⁻² in 2008 and 2009, respectively) than at the Maryland sites (577 and 473 g m⁻² in 2008 and 2009, respectively). From our experience on-station and working on-farm, rye biomass typically does not exceed 600 g m⁻² in our study region unless management is optimized in terms of seeding rate, seeding date, and soil fertility, which can increase biomass up to 1,200 g m⁻². Increasing rye biomass was effective at reducing weed biomass (Figure 2).

In the exponential model describing the reduction in weed biomass as a function of rye biomass (Equation 2), the shape parameter (*b*) represented the strength of weed suppression from rye biomass, with greater coefficients representing greater weed suppression. In this experiment, estimates of the *b* parameter ranged from 0.001 to 0.004 m² g⁻¹ (Table 2). In a previous comparison of different mulch

Table 1. Effects of soybean density on weed biomass across five mulch levels at each site-year fitted to a hyperbolic model.^a

MR	Parameter	Maryland, 2008	Maryland, 2009	Pennsylvania, 2008	Pennsylvania, 2009
0	Intercept (g m ⁻²)	714***	330***	366***	179***
	<i>i</i> _S (m ² plant ⁻¹)	0.062***	< 0.001	0.004	0.053***
	<i>R</i> ²	0.85	0.00	0.01	0.70
0.5	Intercept (g m ⁻²)	693***	364***	343***	121***
	<i>i</i> _S (m ² plant ⁻¹)	0.041***	0.027*	0.142**	0.064
	<i>R</i> ²	0.74	0.34	0.56	0.38
1	Intercept (g m ⁻²)	443***	311***	38**	40**
	<i>i</i> _S (m ² plant ⁻¹)	0.093**	0.095*	0.008	0.016
	<i>R</i> ²	0.62	0.39	0.01	0.02
1.5	Intercept (g m ⁻²)	280***	153***	67***	13*
	<i>i</i> _S (m ² plant ⁻¹)	0.112**	0.358	0.340	0.068
	<i>R</i> ²	0.56	0.39	0.42	0.03
2	Intercept (g m ⁻²)	143***	34*	41***	0
	<i>i</i> _S (m ² plant ⁻¹)	0.056	0.078	0.319	< 0.001
	<i>R</i> ²	0.19	0.12	0.23	0.00

^a Abbreviations: MR, rye mulch rate (a multiplier of the ambient mulch level); intercept (g m⁻²), average weed biomass in the absence of control tactics; *i*, the soybean competition coefficient (m² plant⁻¹); *S*, the soybean density (plants m⁻²).

***, **, and * indicate significance at *P* = 0.001, *P* = 0.05, and *P* = 0.1, respectively.

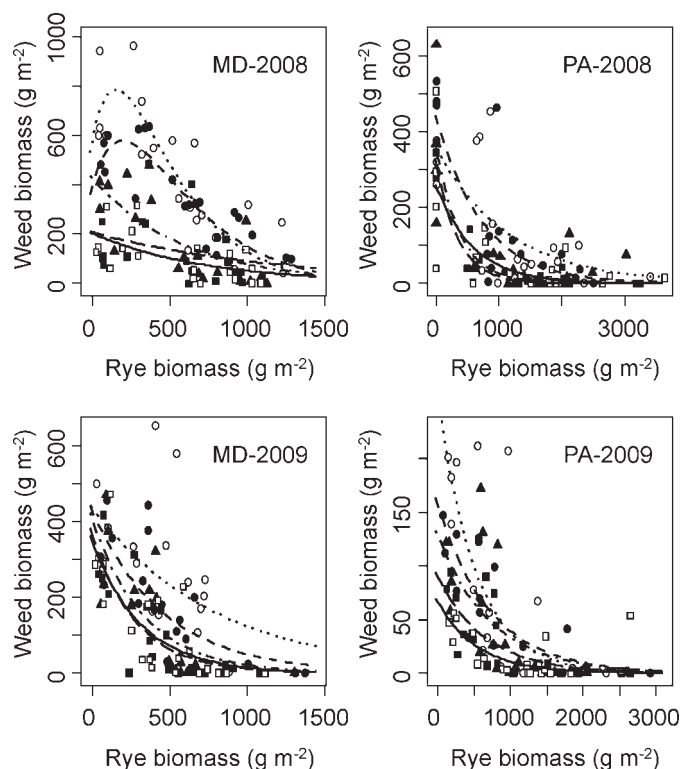


Figure 2. Symbols represent measured weed biomass and rye biomass coordinates and lines represent fitted models for each of the 5 targeted soybean density rates (\circ dotted, 0; \bullet short dash, 19; \blacktriangle dot-dash, 37; \blacksquare long dash, 56; and \square solid line, 74 seeds m^{-2}) across site-years (upper right of each panel). Note the scale of x-axis and y-axis differs between site-years. All data were used for regression analyses; however, axis scales were restricted to illustrate relationships at reasonable rye biomass levels, and thus some extreme data points may not be represented.

materials that included rye residue and other natural and synthetic materials, the b parameter ranged from $0.00009 \text{ m}^2 \text{ g}^{-1}$ with bark on velvetleaf to $0.0126 \text{ m}^2 \text{ g}^{-1}$ for fabric on redroot pigweed (Teasdale and Mohler 2000).

The b parameter estimates ($\text{m}^2 \text{ g}^{-1}$) for rye residue were 0.001, 0.002, 0.002, and 0.004 for velvetleaf, giant foxtail, common lambsquarters, and redroot pigweed, respectively (Teasdale and Mohler 2000), which correspond well to the values observed in this experiment.

Single-Tactic Models as a Family of Regression Curves.

The relationship between weed biomass and soybean seeding rate at each of the five targeted rye biomass levels ($0\times$, $0.5\times$, $1.0\times$, $1.5\times$, and $2.0\times$) is plotted as a family of regression curves (Figure 1). There was a trend toward increasing i parameter values as the rye mulch rate increased in the Maryland in 2009 and Pennsylvania in 2008 experiments, indicating that the weed suppressiveness of soybean was enhanced as rye mulch rate increased.

The relationship between weed biomass and rye mulch rate at each of the five targeted soybean densities (0 , 19 , 37 , 56 , and 74 seeds m^{-2}) is plotted as a family of regression curves (Figure 2). In general an exponential-decay model best described the relationship between rye mulch and weed biomass. There was a trend toward increasing b parameter values with increasing soybean density in Maryland in 2009 and Pennsylvania in 2008, indicating an increased level of weed suppression by rye mulch as soybean density increased. This is an indication that weed suppression by the rye mulch did not function independently of soybean density and that there were potential synergistic interactions between tactics in those site-years.

There was an apparent trend toward decreasing b parameter values in the Maryland-2008 experiment (Table 3); however, that effect was confounded by the presence of a significant m parameter at the low soybean densities. Weed biomass was positively correlated with mulch at rye mulch levels less than 200 g m^{-2} in the no-soybean control and in the lowest soybean density treatment (19 seeds m^{-2}). Stimulation of weeds at low mulch levels was also observed in previous research (Mohler and Teasdale 1993). In one experiment, redroot pigweed emergence increased with legume cover crop

Table 2. Effects of rye biomass on weed biomass across five soybean seeding densities at each site-year fitted to an exponential-decay model.^a

SD	Parameter	Maryland, 2008	Maryland, 2009	Pennsylvania, 2008	Pennsylvania, 2009
0	Intercept (g m^{-2})	580**	435***	358***	258***
	$b_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.004***	0.001*	0.001**	0.002**
	$m_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.009	—	—	—
	R^2	0.71	0.30	0.53	0.54
19	Intercept (g m^{-2})	395**	428***	441***	157***
	$b_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.003***	0.002**	0.001***	0.001***
	$m_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.009	—	—	—
	R^2	0.77	0.55	0.70	0.73
37	Intercept (g m^{-2})	427***	405***	364***	128**
	$b_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.002**	0.003***	0.003*	0.001*
	$m_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	—	—	—	—
	R^2	0.50	0.61	0.70	0.41
56	Intercept (g m^{-2})	208**	363***	324***	89***
	$b_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.001	0.003***	0.003***	0.002*
	$m_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	—	—	—	—
	R^2	0.12	0.67	0.94	0.52
74	Intercept (g m^{-2})	205***	347***	258***	66**
	$b_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	0.001*	0.003**	0.002*	0.002*
	$m_{(R)}$ ($\text{m}^2 \text{ g}^{-1}$)	—	—	—	—
	R^2	0.37	0.60	0.54	0.44

^a Abbreviations: SD, soybean seeding density (seeds m^{-2}); m , a parameter describing a positive effect of rye mulch on weed biomass at low mulch levels ($< 200 \text{ g m}^{-2}$) was included for Maryland in 2008 only, based on the model-selection criteria; intercept (g m^{-2}), the average weed biomass in the absence of control tactics; b , the rye suppression coefficient ($\text{m}^2 \text{ g}^{-1}$); R , the rye biomass (g m^{-2}).

***, **, and * indicate significance at $P = 0.001$, $P = 0.01$, and $P = 0.05$.

Table 3. Parameter estimates for the best two-factor models for each site-year. Models were evaluated using the Akaike's information criterion.^{a,b}

	Maryland, 2008	Maryland, 2009	Pennsylvania, 2008	Pennsylvania, 2009
Intercept [g m^{-2}]	541***	413***	382***	244***
i_S [$\text{m}^2 \text{plant}^{-1}$]	0.057***	0.002	0.006	0.050***
b_R [$\text{m}^2 \text{g}^{-1}$]	0.004***	0.001***	0.001***	0.002***
m_R [$\text{m}^2 \text{g}^{-1}$]	0.011**	—	—	—
$d_{(S \times R)}$ [$\text{m}^4 \text{plant}^{-1} \text{g}^{-1}$]	—	0.00005*	0.00005*	—
R^2	0.78	0.52	0.66	0.58

^a Abbreviations: Intercept (g m^{-2}), the average weed biomass in the absence of control tactics; i , the soybean competition coefficient ($\text{m}^2 \text{plant}^{-1}$); S , the soybean density (plants m^{-2}); b , the rye suppression coefficient ($\text{m}^2 \text{g}^{-1}$); R , the rye biomass (g m^{-2}); m , the rye stimulation ($\text{m}^2 \text{g}^{-1}$), a parameter describing the positive relationship between weed biomass and rye mulch rate, was only included if the estimate was positive and significant; d , the interaction parameter ($\text{m}^4 \text{plant}^{-1} \text{g}^{-1}$).

^b If a parameter was excluded from the best model, a “—” was inserted in the table cell.

***, **, and * indicate significance at $P = 0.001$, $P = 0.01$, and $P = 0.05$.

mulch level until approximately 200 g m^{-2} ; after which, it declined to nearly zero at $1,600 \text{ g m}^{-2}$ (Teasdale and Mohler 2000).

Synergism between Tactics. We set out to test for synergism between tactics by comparing a model with an interaction term to a reference model that was constructed based on a multiplicative relationship between tactics when they were applied in combination. We observed a synergistic interaction in Maryland in 2009 and in Pennsylvania in 2008 (Tables 3 and 4). In site-years where synergy was observed (Pennsylvania-2008 and Maryland-2009), increasing soybean density in the absence of rye mulch did not affect weed biomass (i parameter $P > 0.05$; Table 3). The i parameter was 0.006 and $0.002 \text{ m}^2 \text{plant}^{-1}$ for Pennsylvania-2008 and Maryland-2009, respectively. In the 2 site-years with no interaction between the two tactics, the i parameter values for soybean were an order of magnitude greater (0.057 and $0.050 \text{ m}^2 \text{plant}^{-1}$ at Maryland-2008 and Pennsylvania-2009, respectively). Therefore, the presence or absence of synergism between increasing soybean planting rates and rye mulch rates was dictated by the weed suppressiveness of soybean when no rye mulch was applied.

We included the m parameter when testing for synergy in the Maryland-2008 data set because there was significant stimulation of weed biomass at low rye biomass levels in this site-year. In this case, Equation 7 (interaction model with m parameter) was compared with Equation 6 (reference multiplicative model with m parameter). The interaction term was not significant, and the reference multiplicative model provided a better fit. On the other hand, because the m parameter was most prominent at low, but not high, soybean densities (Figure 2; Table 2), the stimulation of weed biomass at low rye residue levels was itself dependent on the presence or absence of a competitive soybean canopy. Thus, even though there was no overall synergistic interaction detected in the Maryland-2008 experiment according to our criteria,

there was an apparent interaction at low rye residue levels whereby a potential stimulation of weed biomass by low residue levels (perhaps because of enhanced moisture availability under the residue) was suppressed in the presence of moderate to high soybean densities.

The relationship between soybean density, rye biomass, and weed biomass was plotted as a three-dimensional response surface using the final models for each site-year (Table 3; Figure 3). The mulch level required for weed suppression decreases nonlinearly as soybean seeding rate increases across all sites. During the site-years in which a synergistic interaction was observed (Pennsylvania-2008 and Maryland-2009), increasing the soybean seeding rate did not influence weed suppression when this tactic was applied in the absence of rye mulch. However, during site-years with no synergy between tactics, increasing soybean density resulted in a substantial decrease in weed biomass when rye biomass was low. In our experiments, the activation of one tactic (soybean density) that was inactive in the absence of the other tactic (rye mulch) was the driver that defined the synergistic interaction. We suggest that this synergism resulted from the cover crop slowing weed growth early in the season, enough for the suppressive effects of the soybean canopy to be amplified in mid and late season.

The final models describing the relationship between the two tactics and weed biomass for each site-year were plotted as isobolograms. This graphical representation shows the level of each tactic required to suppress a given amount of weeds. Using the parameters presented in Table 3, isobols that represent a 25 and 50% reduction from the mean weed biomass for each site-year were plotted (Figure 4). For example, in Maryland in 2008, a soybean density of 40 plants m^{-2} and a rye biomass level of 600 g m^{-2} resulted in the same weed biomass as a soybean density of 8 plants m^{-2} and 900 g m^{-2} of rye biomass. These soybean density and rye biomass levels correspond to a weed biomass of 123 g m^{-2} , which is 50% of the mean weed biomass for that site-year. Similarly, at a soybean density of 40 plants m^{-2} and 411 g m^{-2} of rye biomass would be required to produce a weed biomass of 184 g m^{-2} , which corresponds to a 25% reduction from the mean weed biomass level for the Maryland-2008 site-year. Isobolograms illustrate the compensatory effect of tactics in combination at different levels and can be useful for interpreting results. For example, the synergistic interaction in Pennsylvania in 2008 and in Maryland in 2009 is represented by disproportionate curvature toward the origin when tactics were combined, compared with the more linear isobols for Maryland in 2008 and for Pennsylvania in 2009.

Table 4. F tests from interaction-model comparisons. Model selection criteria to test for synergy between rye biomass and soybean seeding rate are presented. A more complex model with the interaction parameter was selected if it resulted in an Akaike's information criterion (AIC) reduction of ≥ 2 , the interaction parameter was significant (see Table 3), and the model was different based on an F test. The two-factor interaction model for Maryland-2008 did not converge (DNC).

	Maryland, 2008	Maryland, 2009	Pennsylvania, 2008	Pennsylvania, 2009
ΔAIC	DNC	5.1	8.4	1.8
F ratio	DNC	7	11	4
P value	DNC	0.01	< 0.01	0.64

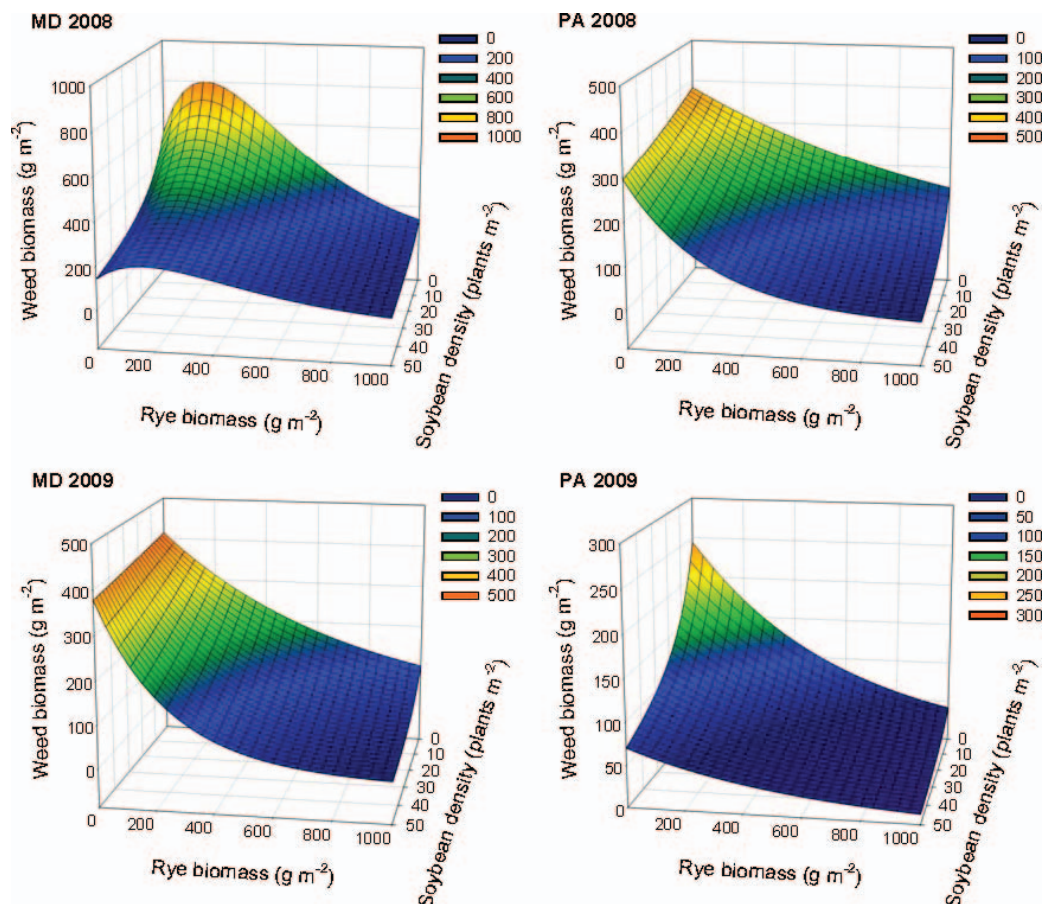


Figure 3. Response surface of weed biomass to rye biomass and soybean density across four site-years using parameter estimates reported in Table 3. Note the scale of y-axis differs between site-years.

Implications. Increasing soybean seeding rate resulted in inconsistent weed suppression. However, variability in suppression was overcome when this tactic was used in conjunction with increasing rye biomass. Recent research has demonstrated agronomic factors, like planting date, termination date (Mirsky et al. 2009), fertility, and cover crop seeding rate (Hunsberger and Ryan 2010), can influence cover crop biomass in predictable ways. Our research builds on this body of knowledge and illustrates the potential for synergistic effects when these tactics are combined with increasing cash crop seeding rates.

In this research, we manipulated rye mulch levels manually and planted into rye stubble (i.e., unmulched soil) so that mulch interference with planting operations and soybean seed placement would not confound the results. Our results demonstrate the principle that soybean population and rye residue can interact synergistically to enhance weed suppression. Application to organic no-till cropping systems will require additional refinements to planter technology to ensure that high crop populations can be consistently achieved when planting soybean into high levels of residue.

Several recent studies have centered on reducing soybean populations to offset the increasing cost of seed due to technology fees (De Bruin and Pedersen 2008; Harder et al. 2007). They argue that because of the high efficacy of glyphosate, additional weed suppression from the soybean crop is unnecessary (Place et al. 2009). Several experiments

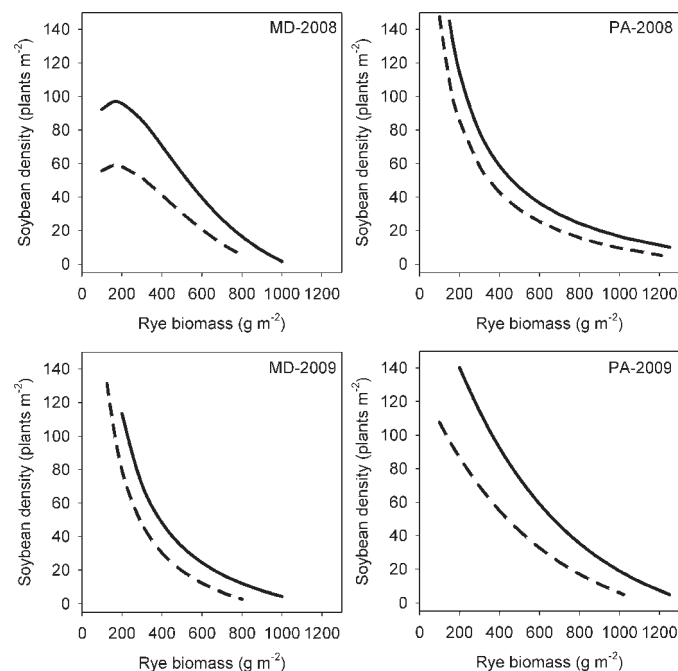


Figure 4. Isobolograms of rye biomass and soybean density required to result in a 25% (dotted line) and 50% (solid line) reduction of the mean weed biomass for each site-year. Mean weed biomass was 246, 157, 115, and 43 (g m^{-2}) for Maryland in 2008, Maryland in 2009, Pennsylvania in 2008, and Pennsylvania in 2009, respectively.

have demonstrated that the economic optimum seeding rate in these systems may be lower than expected, allowing farmers to reduce seed costs and associated technology fees (De Bruin and Pedersen 2008; Harder et al. 2007). In two of the four site-years of our research, increasing soybean density suppressed weeds in the absence of rye residue. This indicates that when soybean seeding rates are lowered to save costs associated with technology fees, farmers may be increasing their reliance on herbicides. In our view, overreliance on any one tactic is the antithesis of robust, sustainable weed management. Within the context of organic rotational no-till soybean production, targeting the optimum crop density/cover crop mulch rate can enhance weed suppression.

In the presence of rye mulch, increasing soybean density decreased weed biomass in all site-years. Thus, despite the inconsistency of weed suppression from increasing soybean density in the absence of mulch, the combination of the tactics effectively and consistently suppressed weeds. Using the final models presented in Table 3, the level of rye mulch needed to suppress weeds varied across site-years. Assuming a standard soybean density of 37 plants m⁻², the level of rye mulch needed to reduce weed biomass to 100 g m⁻² was 699, 403, 401, and 0 g m⁻² for Maryland in 2008, Maryland in 2009, Pennsylvania in 2008, and Pennsylvania in 2009, respectively. Our results demonstrate the importance of synergistic combinations of tactics for compensating for site-years when soybean population alone is not sufficient to suppress weeds.

Trade-offs between the costs of rye and soybean seed and the level of weed suppression achieved from raising seeding rates need to be considered as well. For example, using recent soybean seed prices from 2008, soybean seeds that are not genetically modified organisms (GMOs) could cost \$84 ha⁻¹ when seeded at 37 seed m⁻² (Ellis 2008). Doubling that soybean seeding rate to 74 seed m⁻² to improve weed suppression would increase seed costs to \$168 ha⁻¹. Growers typically face a similar cost increase when they choose to purchase GMO seed, which can easily be double the price of non-GMO seed (Ellis 2008). Cereal rye on the other hand can cost \$52 ha⁻¹ to seed at the standard rate (Wilson 2005) and based on our results, may provide a more effective way to ensure consistent weed suppression than raising soybean seeding rates.

Sources of Materials

¹ Tallman Family Farms, L.L.C., 31 Schwalm Rd., Tower City, PA 17980.

² Blue River Hybrids Organic Seed, 27087 Timber Rd., Kelley, IA 50134.

³ In Maryland and in Pennsylvania-2008, a John Deere 1590 grain drill was used, Deere & Company World Headquarters, One John Deere Place, Moline, IL 61265; and in Pennsylvania-2009, a Great Plains (Solid Stand 10) no-till drill was used, Great Plains Mfg., Inc., 1525 E. North St., Salina, KS 67401.

⁴ R: A Language and Environment for Statistical Computing, Version 2.11.1. R Foundation for Statistical Computing, Vienna, Austria.

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